PREPARATION

1- The Noisy Channel Model

Since TIMS is about modeling communication systems it is not surprising that it can model a communications channel.

Two types of channels are frequently required, namely *low pass* and *bandpass*.

Low pass (or Baseband) channels

A *low pass* channel by definition should have a bandwidth extending from DC to some upper frequency limit. Thus it would have the characteristics of a low pass filter.

A speech channel is often referred to as a low pass channel, although it does not necessarily extend down to DC. More commonly it is called a *baseband* channel.

Bandpass channels

A *bandpass* channel by definition should have a bandwidth covering a range of frequencies not including DC. Thus it would have the characteristics of a bandpass filter.

Typically its bandwidth is often much less than an octave, but this restriction is not mandatory. Such a channel has been called narrow band.

Strictly an analog voice channel is a bandpass channel, rather than low pass, as suggested above, since it does not extend down to DC. So the distinction between baseband and bandpass channels can be blurred on occasion.

Designers of active circuits often prefer bandpass channels, since there is no need to be concerned with the minimization of DC offsets.

Simplification

The above description is an oversimplification of a practical system. It has concentrated all the bandlimiting in the channel, and introduced no intentional pulse shaping. In practice the bandlimiting, and pulse shaping, is distributed between filters in the transmitter and the receiver, and the channel

itself. The transmitter and receiver filters are designed, knowing the characteristics of the channel. The signal reaches the detector having the desired characteristics.

Noise

Whole books have been written about the analysis, measurement, and optimization of signal-to-noise ratio (SNR).

SNR is usually quoted as a power ratio, expressed in decibels. But remember, the measuring instrument in this experiment is an *rms voltmeter*, not a *power* meter.

Although, in a measurement situation, it is the magnitude of the ratio (S / N) which is commonly sought, it is more often (S + N) / N which is available. In other words, in a non-laboratory environment, if the signal is present then so is the noise, the signal is not available only.

In this, and most other laboratory environments, the noise is under our control and can be removed if necessary. So that (S / N), rather than (S + N) / N, can be measure directly.

For high SNRs there is little difference between the two measures.

The noisy channel model

A representative noisy, bandlimited channel model is shown in block diagram form in Figure 1. Band limitation is implemented by any appropriate filter.

The noise is added before the filter so that it becomes bandlimited by the same filter that band limits the signal. If this is not acceptable then the adder can be moved to the output of the filter, or perhaps the noise can have its own bandlimiting filter.

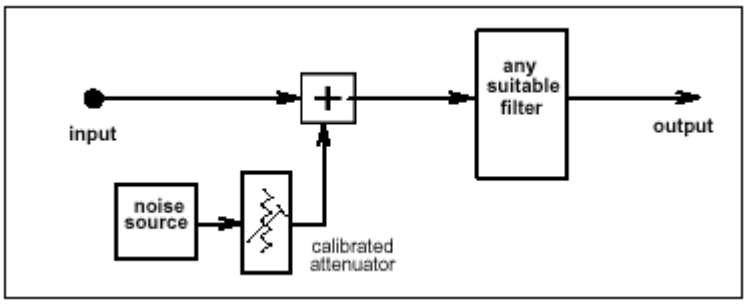

Figure 1: Channel model block diagram

Controllable amounts of random noise, from the noise source, can be inserted into the channel model, using the calibrated attenuator. This is non- signal dependent noise.

For low pass channels low pass filters are used.

For bandpass channels bandpass filters are used.

Signal dependent noise is typically introduced by channel non-linearities, and includes intermodulation noise between different signals sharing the channel (cross talk). Unless expressly stated otherwise, in TIMS experiments signal dependent noise is considered negligible. That is, the systems must be operated under *linear* conditions.

Diagrammatic representation

In patching diagrams, if it is necessary to save space, the noisy channel will be represented by the block illustrated in Figure 2 below.

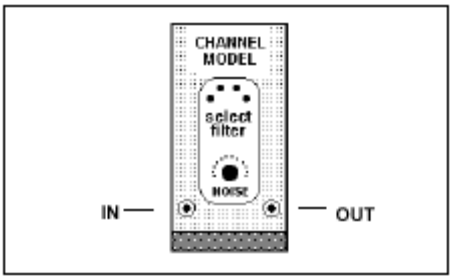

Figure 2: Macro CHANNEL MODEL module

Note it is illustrated as a channel model *module*. Please do not look for a physical TIMS module when patching up a system with this *macro module* included. This macro module is modeled with five *real* TIMS modules, namely:

1. An INPUT ADDER module.
2. A NOISE GENERATOR module.
3. A bandlimiting module. For example, it could be:
    a. Any single filter module; such as a TUNEABLE LPF (for a baseband channel).
    b. A BASEBAND CHANNEL FILTERS module, in which case it contains three filters, as well as a direct through connection. Any of these four paths may be selected by a front panel switch. Each path has a gain of unity. This module can be used in a *baseband*

channel. The filters all have the same *slot* bandwidth (40 dB at 4 kHz), but differing passband widths and phase characteristics.

c. A 100 kHz CHANNEL FILTERS module, in which case it contains two filters, as well as a direct through connection. Any of these three paths may be selected by a front panel switch. Each path has a gain of unity. This module can be used in a *bandpass* channel.

4. An OUTPUT ADDER module, not shown in Figure 1, to compensate for any accumulated DC offsets, or to match the DECISION MAKER module threshold.

5. A source of DC, from the VARIABLE DC module. This is a *fixed module*, so does not require a slot in the system frame.

Thus the CHANNEL MODEL is built according to the patching diagram illustrated in Figure 3 below, and (noting *item 5* above) requires *four* slots in a system unit.

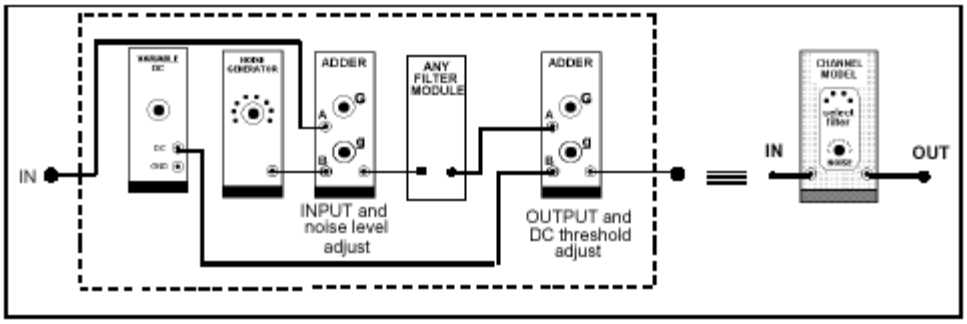

Figure 3: Details of the macro CHANNEL MODEL module

Channel gain

Typically, in a TIMS model, the gain through the channel would be set to unity. This requires that the upper gain control, **'G',** of both ADDER modules, be set to unity. Both the BASEBAND CHANNEL FILTER module and the 100 kHz CHANNEL FILTER module have fixed gains of unity. If the TUNEABLE LPF is used, then its adjustable gain must also be set to about unity.

However, in particular instances, these gains may be set otherwise.

Noise level

The noise level is adjusted by both the lower gain control **'g'** of the INPUT ADDER, and the front panel calibrated attenuator of the NOISE GENERATOR module. Typically the gain would be set to zero **[g** fully anti-clockwise] until noise is required. Then the general noise level is set by g, and *changes* of precise magnitude introduced by the calibrated attenuator.

Theory often suggests to us the means of making small improvements to SNR in a particular system. Although small, they can be of value, especially when combined with other small improvements implemented elsewhere. An improvement of 6 dB in received SNR can mean a doubling of the range for reception from a satellite, for example.

2- Detection with the Decision Maker

The shape of a binary sequence waveform is affected by transmission through a noisy, bandlimited channel. Since the aim of a transmission system is to deliver a perfect copy of the input to the output, the received sequence needs to be restored to its original shape, or *regenerate*d.

The regeneration process is performed by what we will call a *detecto*r.

You should refer to your text book to see the wide range of circuits which has been devised for performing this regeneration process, from the simple amplitude limiter, or the comparator, to extremely sophisticated and intelligent schemes.

As an example of moderate wave shaping, refer to Figure 4, which shows the wave shape changes suffered by a sequence after passage through a bandlimited channel.

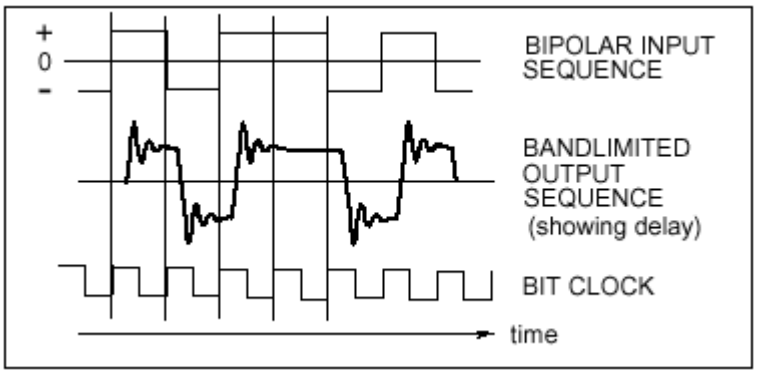

Figure 4: Waveforms before and after moderate bandlimiting

If the bandlimited bipolar output waveform of Figure 4 is connected to a comparator, whose reference is zero volts, then the output will be HI (say +V volt) whilst the waveform is above zero volts, and LO (say -V volt) when it is below. Visual inspection leads us to believe that it is unlikely the comparator would make any mistakes. Examination of the eye pattern of the same waveform would confirm this.

If there was noise, and perhaps further bandlimiting, the comparator would eventually start to fail. But other, more sophisticated circuits, operating on the same waveform, might still succeed in regenerating a perfect copy of the original.

To be fair to the comparator, it is competent to decide whether the signal is *above* (a HI), or *below* (a LO) a reference. Provided the signal-to-noise ratio (SNR) is not too low, then this will be during the HI and LO bits. As the SNR reduces the comparator output may not match favorably the input, especially as regards pulse width. Finally its performance as a *detector* will deteriorate, and extra pulses (or 'bits') will appear, as indicated in Figure 5 below. But note that it is still operating faithfully as a *comparato*r.

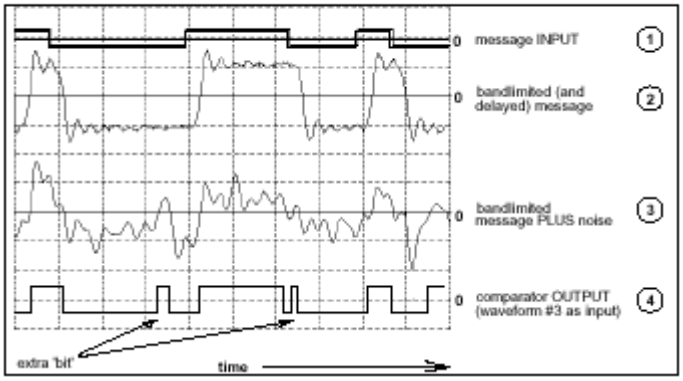

Figure 5: Deterioration of comparator output with noise.

Additional circuitry, using the bit clock as a guide, could be implemented to restore the bit width of the regenerated sequence. This, and more, has been done with the TIMS DECISION MAKER.

The DECISION MAKER is fed a copy of the corrupted sequence, and also a copy of the bit clock. It examines the incoming sequence at a specified *instant* within each bit period. This best *sampling instant* may be chosen by you, after inspection of the eye pattern. With additional external circuitry, this could be automated, or made adaptive.

The DECISION MAKER makes its decision at the instant you have specified within each bit period, and outputs either a HI or a LO. It makes each HI or LO last for a bit period. It also outputs a new bit clock, shifted in time relative to the input bit clock, so that the new clock is aligned with the regenerated bit stream.

The sampling instant, specified by you in this experiment, is set by a front panel control, and is indicated on the oscilloscope waveform by a high intensity spot. The appropriate waveform to be viewing, when selecting the sampling instant, is the *eye patter*n.

For more details about the DECISION MAKER module refer to the ***TIMS User Manual***. You will have an opportunity to become acquainted with it in this experiment. Please note that the circuitry of the DECISION MAKER has been optimized for a clock rate in the region of 2 kHz, so it is unwise to use it at clock rates too far removed from this.

3- BER Measurement in the Noisy Channel

This experiment serves as an introduction to bit error rate (BER) measurement. It models a digital communication system transmitting binary data over a noisy, bandlimited channel. A complete instrumentation setup is included, that allows measurement of BER as a function of signal-to-noise ratio (SNR).

Many variations of this system are possible, and the measurement of the performance of each of these can form the subject of separate experiments.

In this experiment the system is configured in its most elementary form. Other experiments can add different forms of message coding, line coding, different channel characteristics, bit clock regeneration, and so forth.

A simplified block diagram of the basic system is shown in Figure 6 below.

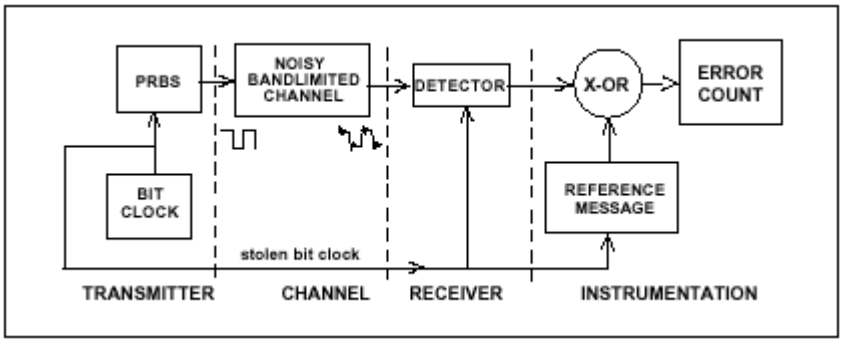

Figure 6: Block diagram of system

The system can be divided into four sections:

Transmitter

At the *transmitter* is the originating message sequence, from a pseudo random binary sequence (PRBS) generator, driven by a system bit clock.

Channel

The *channel* has provision for changing its bandlimiting characteristic, and the addition of noise or other sources of interference.

Receiver

The *receiver* (detector) regenerates the transmitted (message) sequence. It uses a stolen bit clock.

BER instrumentation

The *instrumentation* consists of the following elements:

1. A sequence generator identical to that used at the transmitter. It is clocked by the system bit clock (stolen, in this case). This sequence becomes the reference against which to compare the received sequence.
2. A means of aligning the instrumentation sequence generator with the received sequence. A *sliding window correlator* is used. This was introduced in pervious experiment.
3. A means of measuring the errors, after alignment. The error signal comes from an X-OR gate. There is one pulse per error. The counter counts these pulses, over a period set by a gate, which may be left open for a known number of bit clock periods.

Detailed description

Having examined the overall operation of the basic system, and gained an idea of the purpose of each element, we proceed now to show more of the specifics you will need when modeling with TIMS.

So Figure 6 has been expanded into Figure 7 below.

The detector is the DECISION MAKER module, introduced in this experiment. The LINE-CODE ENCODER and LINE-CODE DECODER modules were introduced in pervious experiment.

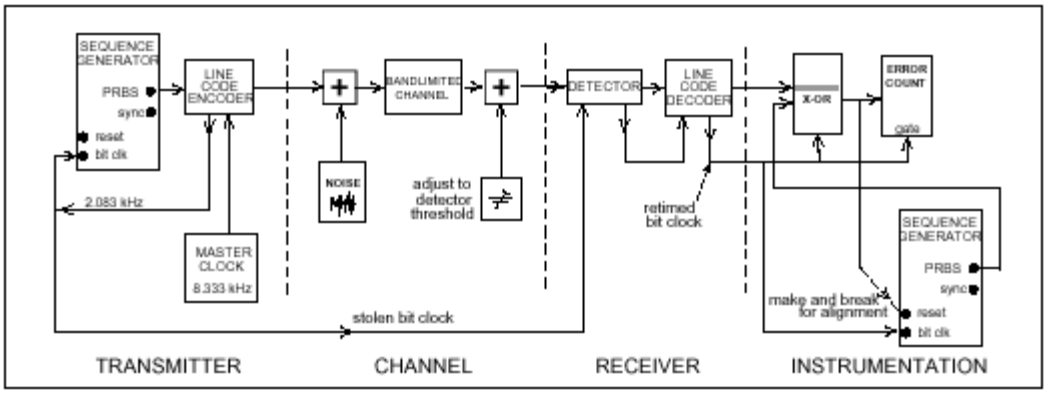

Figure 7: Block diagram of system in more detail

The extra detail in Figure 7 includes:

1. Provision for transforming the data before transmission, using any one of a number of line codes. In this experiment we use the NRZ-L code which provides level shift and amplitude scaling, to suit the analog channel.
2. Bit clock generation. Because the line coder requires quarter-bit-period timing information, it is driven by a *master clock* at four-times the bit-clock rate. The timing information is obtained by dividing the master clock by four (within the LINE-CODE ENCODER). This divided-by-four version of the *master clock* becomes the *system bit clo*ck.
3. Provision for adding noise to the channel via the adder on the *input* side of the bandlimiting channel.
4. Inclusion of an ADDER on the output side of the channel. This restores the polarity change introduced by the input ADDER (for line codes which are polarity sensitive). It also provides an opportunity to fine-trim the DC level to match the threshold of the DECISION MAKER.
5. A decoder for the line code.
6. Instrumentation for SNR adjustment (not shown) and BER measurement.

Theoretical predictions

Bit error probability (P_B) is a function of (E_b / N_0). For matched filter reception of bi-polar baseband signaling it has been shown that:

$$P_B = Q\left(\sqrt{\frac{2E_B}{N_0}}\right)$$

You will measure not P_B, but BER and not (E_b / N_0), but SNR. Figure 8 shows theoretical predictions based on eqn. (1) above.

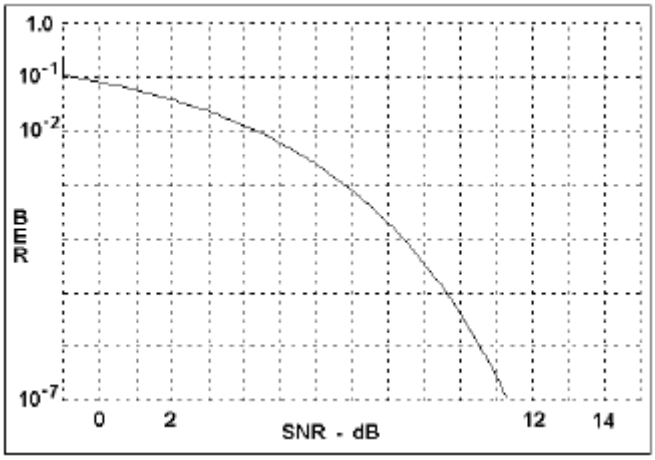

Figure 8 Theoretical expectations - BER versus SNR

(for bi-polar signaling)

EXPERIMENT

1- Filter amplitude response

These days even the most modest laboratory is equipped with computer controlled apparatus which makes the measurement of a filter response in a few seconds, and provides the output result in great detail. At the very least this is in the form of amplitude, phase, and group delay responses in both soft and hard copy.

It is instructive, however, to make at least one such measurement using what might be called 'first principles'. In this experiment you will make a measurement of the amplitude-versus-frequency response of one of the BASEBAND CHANNEL FILTERS.

A typical measurement arrangement is illustrated in Figure 9 below.

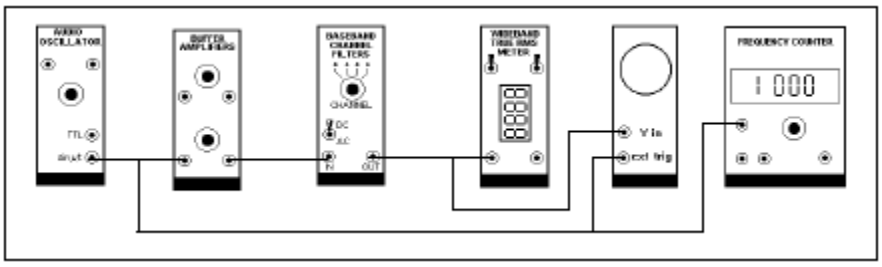

Figure 9: Measurement of filter amplitude response

In the arrangement of Figure 9:

- the audio oscillator provides the input to the filter, at the TIMS ANALOG REFERENCE LEVEL, and over a frequency range suitable for the filter being measured.

- the BUFFER allows fine adjustment of the signal amplitude into the filter. It is always convenient to make the measurement with a constant amplitude signal at the input to the device being measured. The TIMS AUDIO OSCILLATOR output amplitude is reasonably constant as the frequency changes, but should be monitored in this sort of measurement situation.

- the filter can be selected from the three in the module by the front panel switch (positions #2, #3 and #4). Each has a gain in the passband of around unity. Remember there is a 'straight through' path - switch position #1.

- the WIDEBAND TRUE RMS METER will measure the amplitude of the output voltage

- the FREQUENCY COUNTER will indicate the frequency of measurement

- the OSCILLOSCOPE will monitor the output waveform. With TIMS there is unlikely to be any overloading of the filter if analog signals remain below the TIMS ANALOG REFERENCE LEVEL; but it is always a good idea in a less controlled situation to keep a constant check that the analog system is operating in a linear manner - not to big and not too small an input signal. This is not immediately obvious by looking at the WIDEBAND TRUE RMS METER reading alone (see Tutorial Q2). Note that the oscilloscope is externally triggered from the constant amplitude source of the input signal.

The measuring procedure is:

T1 *decide upon a frequency range and the approximate frequency increments to be made over this range. A preliminary sweep is useful. It could locate the corner frequency, and the frequency increments you choose near the corner (where the amplitude-frequency change is fastest) could be closer together.*

T2 *set the AUDIO OSCILLATOR frequency to the low end of the sweep range. Set the filter input voltage to a convenient value using the BUFFER AMPLIFIER. A round figure is often chosen to make subsequent calculations easier - say 1 volt rms. Note that the input voltage can be read, without the need to change patching leads, by switching the front panel switch on the BASEBAND CHANNEL FILTERS module to the straight-through condition - position #1. Record the chosen input voltage amplitude.*

T3 *switch back to the chosen filter, and record the output voltage amplitude and the frequency*

T4 *tune to the next frequency. Check that the input amplitude has remained constant; adjust, if necessary, with the BUFFER AMPLIFIER. Record the output voltage amplitude and the measurement frequency.*

T5 *repeat the previous Task until the full frequency range has been covered.*

The measurements have been recorded. The next step is usually to display them graphically. This you might like to do using your favorite software graphics package. But it is also instructive - at least once in your career - to make a plot by hand, since, instead of some software deciding upon the axis ranges, you will need to make this decision yourself!

Conventional engineering practice is to plot amplitude in decibels on a linear scale, and to use a logarithmic frequency scale. Why?

A decibel amplitude scale requires that a reference voltage be chosen. This will be your recorded input voltage. Since the response curve is shown as a ratio, there is no way of telling what this voltage was from most response plots, so it is good practice to note it somewhere on the graph.

T6 *make a graph of your results. Choose your scales wisely. Compare with the theoretical response.*

2- Signal to noise ratio

This next part of the experiment will introduce you to some of the problems and techniques of signal-to-noise ratio measurements.

The maximum output amplitude available from the NOISE GENERATOR is about the TIMS ANALOG REFERENCE LEVEL when measured over a wide bandwidth - that is, wide in the TIMS environment, or say about 1 MHz. This means that, as soon as the noise is bandlimited, as it will be in this experiment, the rms value will drop significantly.

You will measure both (S / N), (i.e. SNR) and (S + N) / N and compare calculations of one from a measurement of the other.

The un-calibrated gain control of the ADDER is used for the adjustment of noise level to give a specific SNR. The TIMS NOISE GENERATOR module has a calibrated attenuator which allows the noise level to be *changed in small calibrated steps*.

Within the test set up you will use the macro CHANNEL MODEL module already defined. It is shown embedded in the test setup in Figure 10 below.

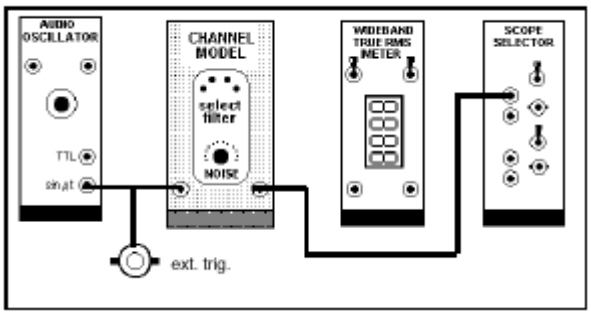

Figure 10: Measurement of signal-to-noise ratio

As in the filter response measurement, the oscilloscope is not essential, but certainly good practice, in an analog environment. It is used to monitor waveforms, as a check that overload is not occurring.

The oscilloscope display will also give you an appreciation of what signals look like with random noise added.

T7 *set up the arrangement of Figure 10 above. Use the channel model of Figure 3. In this experiment use a BASEBAND CHANNEL FILTERS module (select, say, filter #3).*

You are now going to set up independent levels of signal and noise, as recorded by the WIDEBAND TRUE RMS METER., and then predict the meter reading when they are present together. After bandlimiting there will be only a small rms noise voltage available, so this will be set up first.

T8 *reduce to zero the amplitude of the sinusoidal signal into the channel, using the 'G' gain control of the INPUT ADDER.*

T9 *set the front panel attenuator of the NOISE GENERATOR to maximum output.*

T10 *adjust the gain control 'g' of the INPUT ADDER to maximum. Adjust the 'G' control of the OUTPUT ADDER for about 1 volt rms. Record the reading. The level of signal* ***into*** *the BASEBAND CHANNEL FILTERS module may exceed the TIMS ANALOG REFERENCE LEVEL, and be close to overloading it - but we need as*

much noise out as possible. If you suspect overloading, then reduce the noise 2 dB with the attenuator, and check that the expected change is reflected by the rms meter reading. If not, use the INPUT ADDER to reduce the level a little, and check again.

Before commencing the experiment proper have a look at the noise alone; first wideband, then filtered.

T11 *switch the BASEBAND CHANNEL FILTERS module to the straight-through connection - switch position #1. Look at the noise on the oscilloscope.*

T12 *switch the BASEBAND CHANNEL FILTERS module to any or all of the low pass characteristics. Look at the noise on the oscilloscope.*

Probably you saw what you expected when the channel was not bandlimiting the noise - an approximation to wideband white noise.

But when the noise was severely bandlimited there is quite a large change. For example:

a. The amplitude dropped significantly. Knowing the filter bandwidth you could make an estimate of the noise bandwidth before bandlimiting?

b. The appearance of the noise in the time domain changed quite significantly. You might like to repeat the last two tasks, using different sweep speeds, and having a closer look at the noise under these two different conditions.

Record your observations. When satisfied:

T13 *reduce to zero the amplitude of the noise into the channel by removing its patch cord from the INPUT ADDER, thus not disturbing the ADDER adjustment.*

T14 *set the AUDIO OSCILLATOR to any convenient frequency within the passband of the channel. Adjust the gain 'G' of the INPUT ADDER until the WIDEBAND TRUE RMS METER reads the same value as it did earlier for the noise level.*

T15 *turn to your note book, and calculate what the WIDEBAND TRUE RMS METER will read when the noise is reconnected.*

T16 *replace the noise patch cord into the* INPUT *ADDER. Record what the meter reads.*

T17 *calculate and record the signal-to-noise ratio in dB.*

T18 *measure the signal-plus-noise, then the noise alone, and calculate the SNR in dB. Compare with the result of the previous Task.*

T19 *increase the signal level, thus changing the SNR. Measure both (S / N) and (S + N) / N and predict each from the measurement of the other. Repeat for different SNR.*

2- Decision Maker

You will examine the decision process applied to a noisy bandlimited bipolar waveform using two methods: a basic COMPARATOR (un-gated), and the TIMS DECISION MAKER module. In next section you will count actual errors, but for now evaluation will be by visual comparison of the device output and the original sequence.

Test signal

The test signal will come from a SEQUENCE GENERATOR via a noisy, bandlimited channel. The bandlimiting of the channel will be adjustable. This is illustrated in block form in Figure 11 below.

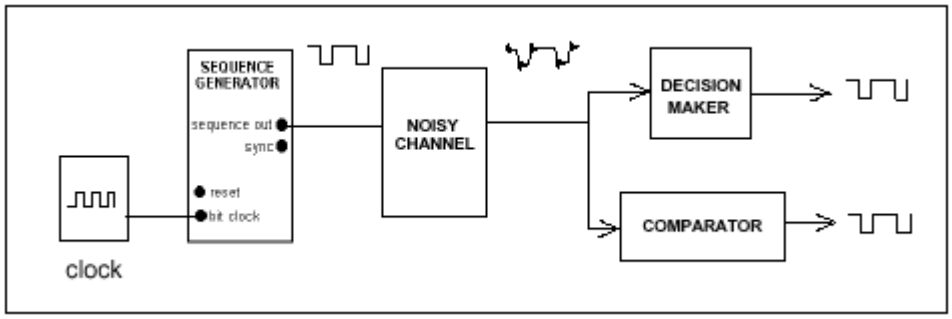

Figure 11: System to demonstrate sequence regeneration

A model of the block diagram of Figure 11 is shown in Figure 12 below. It uses the macro CHANNEL MODEL module. Use *Tunable LPF* module as band limiting channel.

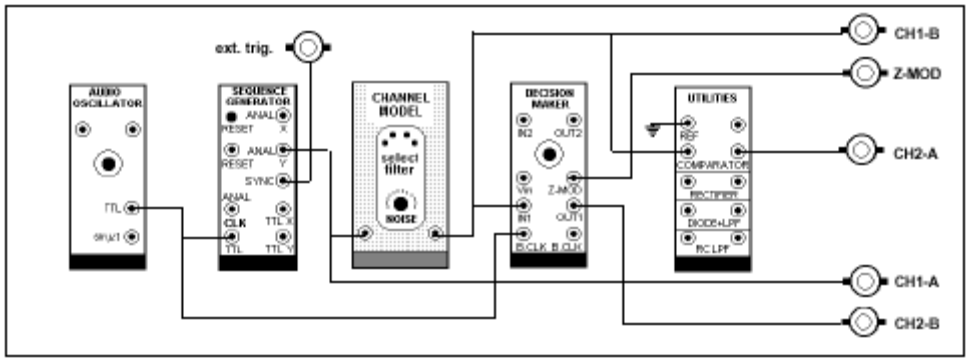

Figure 12: COMPARATOR and DECISION MAKER as regenerators

Signal regeneration

First patch up the complete system, according to the block diagram of Figure 11, shown modeled in Figure 12.

note that:

- for selecting the best sampling instant the *eye pattern* is preferred. The oscilloscope is triggered externally by the bit clock.

- to check, visually, that the recovered sequence is error free, you need the *snapsho*t. The oscilloscope is triggered externally by the SYNC pulse of the SEQUENCE GENERATOR.

Ideally, for *visual* evaluation, the first of these requires a *long* sequence, and the second a *short* sequence. For convenience, however, you may find it acceptable to use *short* sequence for both observations.

T20 *before plugging in the SEQUENCE GENERATOR module select the minimum length sequence with the on-board switch SW2 (both toggles UP).*

T21 *model the complete system illustrated in Figure 12, except for the DECISION MAKER.*

T22 *set the AUDIO OSCILLATOR to about 2 kHz. This will suit the DECISION MAKER, which has been designed for operation with clock rates of this order.*

T23 *ensure the oscilloscope is triggering on the SYNC signal from the SEQUENCE GENERATOR. Check the sequence on CH1-A.*

Using the COMPARATOR

T24 *set the TUNEABLE LPF to its widest bandwidth. Check the signal on CH1-B is roughly of the same shape as shown in Figure 4. The COMPARATOR should have no trouble regenerating this sequence.*

T25 *check the COMPARATOR output against the original sequence by looking at CH1-A and CH2-A simultaneously. Satisfy yourself that regeneration is acceptable.*

T26 *now carry out some observations of the COMPARATOR output as either or both the channel bandwidth is varied and noise is added. Get some appreciation of the limitations of the COMPARATOR as a regenerator.*

Signal levels

No mention was made above about the signal levels at the various interfaces. You should be experienced enough now to realize how important these are. Although this may seem to be a *digital-style* experiment, most of the modules are processing *analog-level* signals. So the signal levels at their (yellow) interfaces should be adjusted appropriately. That is, they should be at about the TIMS ANALOG REFERENCE LEVEL, or 4 volt peak-to-peak. Check back that this was achieved.

DC threshold

You can investigate the purpose of the DC threshold adjustment provided in the CHANNEL MODEL. Slowly reduce the channel output amplitude, whilst monitoring the COMPARATOR output. Eventually, as the signal amplitude is progressively decreased, the COMPARATOR output will be all HI or all LO. Fine adjustment of the DC level from the channel 1 will re-position the sequence with respect to the COMPARATOR reference level (nominally zero, or ground) and allow operation for even smaller input levels.

Using the DECISION MAKER:

T27 *read about the DECISION MAKER module in the* ***TIMS User Manual****. Before plugging it in, ensure that:*

a) *The on-board switch SW2 is switched to 'INT'*

b) *The 'NRZ-L' waveform is selected with on-board switch SW1(upper rear of board). This configures the DECISION MAKER to accept bipolar non-return-to-zero waveforms, as you have from the analog output of the SEQUENCE GENERATOR.*

T28 *change the oscilloscope triggering, and display an eye pattern.*

T29 *patch the DECISION MAKER into the system, including the Z-MOD connection to the oscilloscope.*

T30 *rotate the front panel DECISION POINT control knob of the DECISION MAKER. There should be a highlighted point moving across both oscilloscope traces. If the spot cannot be seen, try varying the oscilloscope intensity control. If still no spot, seek help from your Laboratory Manager. As a last resort (!) refer to the* ***TIMS User Manual*** *and the oscilloscope User Manual. There are settings on the DECISION MAKER circuit board to suit most oscilloscopes, and once set (by the Laboratory Manager) they require no further adjustment.*

note*: make sure a TTL bit clock is connected to B.CLK in.*

T31 *locate the high intensity spot on the oscilloscope display. This shows the sampling instant.*

T32 *adjust the front panel control of the DECISION MAKER so that the sampling instant is positioned at the best decision point within the bit period; i.e., where the vertical eye opening is greatest.*

T33 *the regenerated sequence will be displayed on CH2-B. Compare it with the input sequence on CH1-A. There will, of course, be a time offset between the two, due to the delay introduced by the filter, and the regeneration process itself.*

Note that the DECISION MAKER provides a new bit clock, aligned with the regenerated sequence. This is essential for later processing of the regenerated sequence (e.g, by the error counter - see later).

You will now make some more demanding tests of the DECISION MAKER.

Changing from one display to the other involves a little more than changing the connection to the ***ext trig*** of the oscilloscope, as generally the sweep speed needs some slight adjustment. Ideally, also, the snapshot needs a short sequence, and the eye a long sequence. But for these tests a short sequence should be acceptable for both.

What you will have to do, each time you make a test, is:

1. Lower the bandwidth a little
2. Re-position the sampling instant
3. Check the sequences for equality

You can develop your own visual scheme for comparing sequences.

T34 *now carry out some observations of the DECISION MAKER output, as you did for the COMPARATOR output, as either or both the channel bandwidth is varied and noise is added. Get some idea of the performance of the DECISION MAKER, as compared with that of the simple COMPARATOR, as a regenerator.*

ERROR COUNTING UTILITIES module

This is the first time the pulse counting capabilities of the ERROR COUNTING UTILITIES module have been used. A complete description of the characteristics and behavior of the module can be obtained from the *TIMS Advanced Modules User Manua*l.

3- BER Measurement

The system to be modeled is shown in Figure 13. It will be patched up systematically, section by section, according to the scheme detailed below. It has not been cluttered by showing oscilloscope connections. You should set up the SCOPE SELECTOR for maximum usage of the facility for toggling between the A and B options for each channel.

Remember that, during testing, and afterwards, the oscilloscope triggering comes from:

- the SYNC output from the transmitter SEQUENCE GENERATOR for snapshots
- the bit clock for eye patterns.

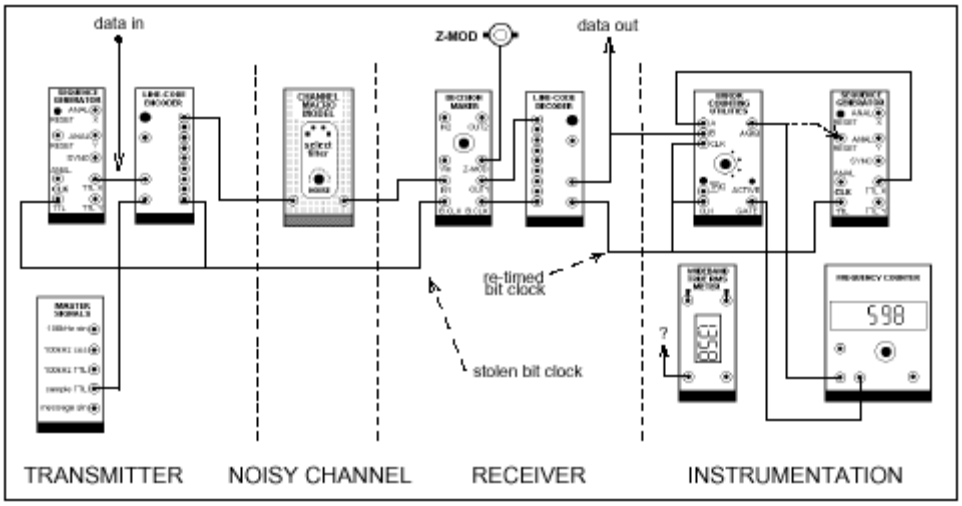

Figure 13: TIMS model of Figure 7

1.0: Transmitter

T1.1 *patch the transmitter according to Figure 13, from a SEQUENCE GENERATOR (set to a short sequence - both toggles of SW2, on circuit board, UP), a LINE-CODE ENCODER (using NRZ-L), and the MASTER SIGNALS module. Note that the LINE-CODE ENCODER accepts the* ***master clock****, which is the 8.333 kHz*

TTL 'sample clock' from the MASTER SIGNALS module, and divides it by four to produce the 2.083 kHz ***system bit clock*** *for the SEQUENCE GENERATOR.*

T1.2 *press the reset on the LINE-CODE ENCODER. Check on CH1-A that a short TTL sequence has been generated by the SEQUENCE GENERATOR.*

T1.3 *simultaneously with the previous observation on CH1-A, check the NRZ-L output of the LINE-CODE ENCODER on CH2-A. Relative to the TTL on CH1-A it will be delayed half a bit period. This is the signal being transmitted to the channel. Confirm the code format.*

2.0: Channel model

The macro CHANNEL MODEL module is shown modeled in Figure 3.

T2.1 *patch up the channel according to Figure 4 and insert it into the position shown in Figure 13. Use "Baseband Channel filter" module in the channel macro model.*

T2.2 *set the front panel attenuator of the NOISE GENERATOR to maximum output; but reduce the channel noise to zero by rotating the* INPUT *ADDER gain control* ***'****g'* *fully anti-clockwise.*

T2.3 *adjust the amplitude of the signal* ***into*** *the BASEBAND CHANNEL FILTERS module to near the TIMS ANALOG REFERENCE LEVEL (say, 2 volt peak-to-peak) with the* INPUT *ADDER gain control* ***'****G'. This level will need resetting when noise is added.*

T2.4 *select channel #3 of the BASEBAND CHANNEL FILTERS module.*

T2.5 *set the gain of the DC threshold adjustment path through the* OUTPUT *ADDER to zero.*

T2.6 *check that the amplitude of the signal* ***out of*** *the CHANNEL MODEL to is around 2 volts peak-to-peak. If not adjust it with the* OUTPUT *ADDER gain control 'G'. The gain through the channel is now unity.*

T2.7 *confirm that the signal at the* OUTPUT *ADDER, although of different shape, and further delayed, is clearly related to the input sequence.*

When tracing the sequence through the system, notice that there is a polarity inversion introduced by the INPUT ADDER of the channel, and a second inversion introduced by the OUTPUT ADDER.

3.0: Receiver

The receiver consists of the DECISION MAKER and LINE-CODE DECODER modules.

T3.1 *before plugging in the DECISION MAKER:*

a) Switch the on-board switch SW2 to 'INT' (DECISION POINT can now be adjusted with the front panel control).

b) *Select the expected line code with the on-board rotary switch SW1 (upper rear of board). For this experiment it is NRZ-L.*

T3.2 *patch up the DECISION MAKER, including the Z-MOD output to the oscilloscope. It is assumed that the Z-MOD adjustments have been made on the circuit board to suit your oscilloscope.*

T3.3 *trigger the oscilloscope from the bit clock, and obtain an eye pattern at the channel output. Adjust the sampling instant, with the DECISION MAKER front panel control, to the center of the eye. Remember that some fine adjustment of the intensity control of the oscilloscope will probably be necessary to easily identify the bright spot at the sampling instant.*

T3.4 *trigger the oscilloscope from the* SYNC *output of the transmitter SEQUENCE GENERATOR. Check that the reconstructed 'analog' output from the DECISION*

MAKER is a delayed version of, but otherwise the same shape as, that at the channel input.

T3.5 *refer to the DECISION MAKER in the* ***TIMS User Manual*** *for threshold level information. This varies according to the code in use. For the NRZ-L code the threshold is approximately 25 mV. Thus the input signal amplitude must either swamp any possible DC threshold, or, if small, must be adjusted to straddle it. There is provision in the model (the OUTPUT ADDER) for this; it will be checked in the next Section. For now confirm that the output waveform is centered approximately about zero volts.*

T3.6 *patch up the LINE-CODE DECODER, selecting the NRZ-L output.*

T3.7 *press the reset on the LINE-CODE DECODER. Check that the TTL output sequence is identical, except for a delay, with that at the transmitter SEQUENCE GENERATOR output.*

Do not proceed unless these two TTL signals are identical!

4.0: BER measurement instrumentation

The transmission system is now fully set up. You will now proceed to verify its overall operation.

The BER measurement instrumentation system is used to generate an *identical* sequence to that transmitted, and *aligned* with that from the receiver detector. These two sequences will be compared, bit by bit, and any disagreements *counte*d. The count is made over a pre-determined number of bit clock periods, and so the bit error *rate* (BER) may be calculated.

You will record the BER for various levels of noise, and compare with theoretical expectations.

T4.1 *patch up according to Figure 13. Note the instrumentation (receiver) SEQUENCE GENERATOR uses the LINE-CODE DECODER strobe as its bit clock. Trigger the oscilloscope for a snapshot. Check that there is a short sequence coming from the instrumentation SEQUENCE GENERATOR output.*

T4.2 *see the Appendix to this experiment for a short description of the ERROR COUNTING UTILITIES module, including on-board jumper and switch settings. Plug it in. Check that the line from the X-OR output to the instrumentation SEQUENCE GENERATOR RESET is* ***open****.*

T4.3 *observe the two inputs to the X-OR gate simultaneously. It is unlikely that they are aligned, but they should be synchronized.*

Your good work is about to be rewarded with the sight of the two sequences snapping into alignment.

T4.4 *momentarily close the line from the X-OR output to the instrumentation SEQUENCE GENERATOR RESET. Confirm that the two sequences, already synchronized, are now aligned. If you want to see the sliding window correlator at work again, press the reset on the instrumentation SEQUENCE GENERATOR, and alignment will be lost. Re-align by repeating the last Task.*

T4.5 *set the FREQUENCY COUNTER to its COUNT mode, and patch it into the system, complete with the gate signal from the ERROR COUNTING UTILITIES module.*

T4.6 *switch the gate of the ERROR COUNTING UTILITIES, with the PULSE COUNT switch, to be active for* 10^5 *bit clock periods. Make a mental calculation to estimate how long that will be!*

T4.7 *to make an error count:*

a) Reset the FREQUENCY COUNTER.

b) Start the error count by pressing the TRIG button of the ERROR COUNTING UTILITIES module.

The 'active' LED on the ERROR COUNTING UTILITIES module will light, and remain alight until 90% of the count is completed, when it will blink before finally extinguishing, indicating the count has concluded.

With no noise there should be no errors. But .....

warning: every time a count is initiated *one count* will be recorded immediately. This is a 'confidence count', to reassure you the system is active, especially for those cases when the actual errors are minimal. It does *not* represent an error, and *should always be subtracted from the final count*.

Despite the above single confidence-count you may wish to make a further check of the error counting facility, before using noise.

T4.8 *if the ERROR COUNTING UTILITIES GATE is still open press the instrumentation SEQUENCE GENERATOR reset button (else press the TRIG to open the GATE). The sequences should now be out of alignment.*

The counter will start counting (and continue counting) errors until the GATE shuts. It will record a count of between 2 and 10^n (with the PULSE COUNT switch set to make 10^n counts). You will record a different count each time this is repeated. Why would this be?

You have just completed a major setting-up procedure. If it was achieved without any problems you are to be congratulated! Although TIMS itself will behave reliably, it is easy to make patching errors, and their discovery and rectification is all part of the learning process.

5.0 Error counting with noise preparation

T5.1 *increase the message sequence length of both SEQUENCE GENERATOR modules (both toggles of SW2 DOWN).*

T5.2 *re-establish sequence alignment by pressing all the reset buttons, in order input to output, then momentarily connect the X-OR output to the instrumentation SEQUENCE GENERATOR RESET input.*

Adding noise - principle

It is now time to add the noise to the signal. Noise must be introduced *before* bandlimiting, since the channel bandlimiting filters are required to bandlimit the noise as well.

The noise from the NOISE GENERATOR is wideband. Its peak amplitude must not overload an analog module, so its output has been restricted to 4 volt peak-to-peak (the TIMS ANALOG REFERENCE LEVEL). As soon as it is bandlimited, this amplitude is reduced. Amplification cannot be used to bring it up to a convenient level until *after* bandlimiting. But by this time the signal has been added, so that is not possible.

So the only way to obtain a small signal-to-noise ratio (relatively high noise) is to *reduce* the signal level. This is done with the INPUT ADDER.

To set the noise level:

a) Remove the signal from the channel input

b) Add as much noise as is available, to implement the worst SNR possible, by maximizing the gain through the INPUT ADDER, and setting the attenuator of the NOISE GENERATOR for maximum noise output. The SNR can later be increased - less noise - with this attenuator.

c) Measure the noise level into the DECISION MAKER with the WIDEBAND TRUE RMS METER. Then remove the noise, replace the signal, and adjust it to the same level.

d) Replace the noise. The SNR is 0 dB.

The system is now set up for the worst conditions under which measurements are to be made. From now on the SNR will be improved, in *calibrated* steps of the NOISE GENERATOR attenuator, and BER measurements recorded.

The above steps will now be implemented.

Adding noise - practice

T5.3 *patch both the oscilloscope and the WIDEBAND TRUE RMS METER to observe the signal at the* ***output*** *of the channel.*

T5.4 *reduce the signal amplitude to zero with the 'G' gain control of the INPUT ADDER.*

T5.5 *set the attenuator of the NOISE GENERATOR for maximum output. Increase the noise level* ***into*** *the channel, with the INPUT ADDER, to maximum.* ***Record the reading of the rms meter (N volt rms amplitude****).*

T5.6 *remove the noise by unplugging the patch cord from the INPUT ADDER.*

T5.7 *introduce some signal with the 'G' control of the channel INPUT ADDER, until the rms meter is reading the same as the previous noise reading.* ***Record this reading (S volt rms amplitude****).*

T5.8 *replace the noise. Do not disturb the INPUT ADDER gain settings from now on!*

T5.9 *check the signal level at the channel output. Use the 'G' gain control of the OUTPUT ADDER to raise the input level to the DECISION MAKER to the TIMS ANALOG REFERENCE LEVEL (4 V peak-to-peak is allowable, although there may be insufficient gain in the ADDER).*

The SNR is now set up to a reference value $10\log_{10}\left(\frac{S}{N}\right)$ ***dB***

and this will be 0 dB. However you may have your own reasons for selecting some other ratio, but it needs to result in many errors. From now on you can only *reduce* the noise, using the calibrated attenuator of the NOISE GENERATOR. This will *increase* the SNR, which will in turn *reduce* the error rate.

warnin*g: if alignment is ever lost the noise must be removed before attempting re-alignment !*

T5.10 *set the SNR to, say, 10 dB, and set the decision instant with the aid of an eye pattern.*

6.0 DC threshold adjustment

The effect of any DC threshold of the DECISION MAKER must be offset with DC introduced by the OUTPUT ADDER.

Two methods are suggested.

1. After setting up as above, add a small DC to the signal from the channel. If the error count can be reduced then adjust for the smallest count.
2. Set the DC output from the channel to +25 mV. This is the threshold level of the DECISION MAKER in NRZ-L mode.

Now implement one or the other method of threshold adjustment.

Method #1

T6.1 *set the PULSE COUNT on the DECISION MAKER to* 10^5 *and press the TRIG button. Adjust the noise level with the attenuator so that errors are accumulating at about 10 per second (watch the second last digit).*

T6.2 *rotate the VARIABLE DC level about* 45^0 *anti-clockwise. Advance the 'g' control of the OUTPUT ADDER about* 20^0 *. The error rate should increase.*

T6.3 *slowly reduce the DC offset voltage magnitude (rotate the VARIABLE DC control clockwise towards zero). The error rate should slowly reduce, then increase. Return to the lowest rate and stay there. This is an important adjustment. It takes some practice. At all times set the error rate (with the noise source attenuator) so it is about 10 errors per second. Concentrate on the second last, and then the last digit, as the minimum is approached.*

Method #2

T6.4 *remove both inputs from the INPUT ADDER. Using both the VARIABLE DC control and the OUTPUT ADDER 'g' control, set the DC level at the input to the DECISION MAKER +25 mV (use the WIDEBAND TRUE RMS METER). Replace the inputs to the INPUT ADDER.*

*M*easuring the BER

Everything is now set up for some serious measurements. It is assumed that:

- both SEQUENCE GENERATORS are set for long sequences (both toggles of the on-board switch SW2 are DOWN).
- line code NRZ-L has been patched (for *this* experiment) on the LINE-CODE ENCODER and LINE-CODE DECODER.
- line code NRZ-L has been selected with SW1 on the DECISION MAKER board.
- all reset button have been pushed (in turn from input to output).
- levels throughout the system have been set correctly (typically with SNR = 0 dB with max noise from the NOISE GENERATOR).
- DC threshold at the DECISION MAKER has been accounted for.
- signal into the DECISION MAKER is ideally at the TIMS ANALOG REFERENCE LEVEL.
- the DECISION POINT of the DECISION MAKER has been set up, using an eye pattern (with 'moderate' noise present - say an SNR of 10 dB).
- the SEQUENCE GENERATOR at the receiver has been aligned with the incoming sequence (carried out with no noise present - a high SNR).
- conditions for a known (reference) SNR are recorded.
- channel bandwidth is recorded (e.g., which filter of the BASEBAND CHANNEL FILTERS module is in use).

T6.5 *measure BER according to the procedure in Task T4.7. Record the measurement, and the conditions under which it was made. Compare results with counts over short and long periods.*

T6.6 *decrease the noise level by one increment of the NOISE GENERATOR front panel attenuator. Go to the previous Task. Loop as many times as appropriate.*

T6.7 *plot BER versus SNR. Relate your results to expectations.*

TUTORIAL QUESTIONS

Q1 *an analog channel is overloaded with a single sine wave test signal. Is this always immediately obvious if examined with an oscilloscope? Is it obvious with:*

a) A single measurement using a voltmeter?

b) Two or more measurements with a

voltmeter? Explain you answers to (a) and (b).

Q2 *suppose an rms voltmeter reads 1 volt at the output of a noisy channel when the signal is removed from the input. What would it read if the bandwidth was halved? State any assumptions which were necessary for this answer.*

Q3 *a sinusoidal waveform has a peak-to-peak amplitude of 5 volts. What is its rms value?*

Q4 *what would an rms meter read if connected to a square wave:*

a) Alternating between 0 and 5 volt?

b) Alternating between ±5 volt?

Q5 *the measuring instrument used in this experiment was an rms volt meter. Could you derive a conversion factor so that the instrument could be used as a direct reading (relative) power meter?*

Q6 *suppose a meter is reading 1 volt rms on a pure tone. Wideband noise is now added until the meter reading increases by 10%.*

a: What would be the signal-to-noise ratio in dB ?

b: What would the rms volt meter read on noise alone ?

This answer is meant to show that measuring small changes to signal-to-noise ratios is difficult unless the signal-to-noise ratio is already small. Do you agree? How small?

Q7 *wideband white noise is passed through a low pass filter to a meter. If the filter bandwidth is decreased by one half, what would be the change of the reading of the meter if:*

a) It responds to power - answer in dB

b) It is a true rms volt meter - give the percent change

Q8 *explain how you might measure, or at least demonstrate the existence of, a time delay through any of the filters?*

Q9 *familiarize yourself with the terms 'timing jitter' and 'baseline wander'. Explain, via the eye pattern, how these affect the satisfactory operation of the detection device.*

Q10 *once sequence alignment is attained, the sliding window correlator is disabled. Explain why alignment is not lost even if the noise level is raised until the BER increases to unacceptably high levels.*

Q11 *why were you advised to use a long sequence when counting errors?*

Q12 *explain the principle of what you were doing when adjusting the DC at the input to the DECISION MAKER.*

APPENDIX

ERROR COUNTING UTILITIES module

A full description of this module is available in the *TIMS Advanced Module User Manua*l. This should be essential reading before the module is used.

Before use it is necessary to check the settings of the on-board switches SW1 and SW2, and the jumper J1.

Briefly, the module consists of two sub-systems:

X-OR gate

This has two modes:

1. *pulse mode:* with a clock signal connected. Acts as a gated sub-system. Somewhere near the middle of each clock pulse it makes an X-OR decision regarding the two TTL inputs. Its output is a TTL HI if they are different, otherwise a LO. In the present application it compares each bit of the regenerated received signal with a reference generator. Differences – which represent errors - are counted by the FREQUENCY COUNTER in COUNT mode.
2. *normal mod*e: with no clock input

gate timing pulse

This clocked sub-system, on receipt of a trigger pulse - manual or electronic –outputs a pulse of length (number of clock periods) determined by the front panel switch PULSE COUNT, the toggles of the on-board switch SW2, and jumper J1. In this experiment the trigger pulse is initiated by the front panel TRIG push button.

The GATE output pulse (a LO, selected by toggle 2 of the on-board switch SW1) is used to activate the FREQUENCY COUNTER, in COUNT mode.

on-board settings for this

switch/jumper	*toggle*	*position*	*comments*
J1		NORM	
SW1	1 - TRIG	HI - to left	suits press button
SW1	2 - GATE	LO - to right	counter activated on LO
SW2	1	ON - to right	PULSE COUNT switch settings times unity
SW2	2	ON - to right	